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(71)(72) Applicants and Inventors: MILEY, George, H. [US/US]; 914 West Armory Drive, Champaign, IL 61821 (US). JURCZYK, Brian, E. [US/US]; 506 West Griggs Street #102, Urbana, IL 61801 (US). GU, Yibin [CN/US]; 2503 West Springfield, Champaign, IL 61821 (US). STUBBERS, Robert, A. [US/US]; 106 South Coler #22, Urbana, IL 61801 (US). WILLIAMS, Michael, J. [US/US]; 807 West James Court, Mahomet, IL 61853 (US).

(74) Agents: KASPER, Alan, J. et al.; Sughrue, Mion, Zinn, MacPeak & Seas, PLLC, Suite 800, 2100 Pennsylvania Avenue, N.W., Washington, DC 20037-3202 (US).

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(54) Title: INERTIAL ELECTROSTATIC CONFINEMENT (IEC) FUSION DEVICE WITH GATE-VALVE PULSING

(57) Abstract

A pulsed neutron/proton source based upon the design of a steady-state spherical inertial electrostatic confinement (IEC) configuration and using a pulsed gate valve grid (GVP). The IEC-GVP device comprises a grounded conductive vessel, serving as an anode, and a central cathode or primary grid that is connected to a high voltage source. In addition, an intermediate second grid and an outside third grid are disposed concentrically with the central cathode within the vessel. Electron extractor/emitter devices are disposed substantially symmetrically about the perimeter of the vessel and include electron extractor deflector grids and electron emitters that contribute to the enhanced timed ion flow in the device. Two techniques for pulsing the second grid are used. A first is a low repetition rate GVP (LR-GVP) operation and a second is a tuned high-frequency pulsing, termed Resonant Ion Driven Oscillation (RIDO) GVP operation.

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INERTIAL ELECTROSTATIC CONFINEMENT (IEC) FUSION DEVICE WITH GATE-VALVE PULSING

BACKGROUND OF THE INVENTION

This application claims domestic priority from U.S. Provisional Application SN 60/064,801 filed November 12, 1997, and the entire content of that application is incorporated herein by reference.

An Inertial Electrostatic Confinement (IEC) device for use as a steady-state 2.5-MeV D-D neutron source in applications such as Neutron Activation Analysis (NAA) is known, and a spherical IEC configuration was previously disclosed in US patent application SN 08/730,578, which is a continuation of application SN 08/232,764, now abandoned, both of which are incorporated herein by reference. The IEC device 1, as seen in Fig. 1, comprises a spherical vacuum chamber 2, serving as a grounded anode and having several ports, including a gas input port 3 that is connected to a gas source (not shown) via a gas feed line 4 and a valve 5. The gas input to the vessel is a fusionable gas comprising a single component or a mixture of components such as deuterium, tritium and He-3. A second port 6 is connected to a vacuum pump (not shown), and a third port 7 is connected to a high voltage power supply 8 via a high voltage feedthrough 9. A grid 10 at the center of

the sphere 2, which may be a wire or vane type structure, has a geometric transparency of preferably 80-97% and is connected to the high voltage source 8, which provides a negative high voltage potential that serves to initiate and maintain a discharge. This, in effect, operates as an ion-accelerator, plasma-target unit. An off-the-shelf commercial version now provides a portable, long-lived neutron source with steady-state production levels of 10^6 - 10^7 n/s. Due to its low cost, safety and licensing advantages, these commercial IEC units are intended to replace existing NAA neutron sources such as Californium-252, and small accelerator solid-target units.

In operation, a non-neutral, non-Maxwellian plasma is created in an IEC by energetic ions that are accelerated and focussed at a center spot by the spherical grid 10, centered in a vacuum vessel as shown in Figure 1. After filling the vacuum chamber with the selected gas at the desired pressure ($\lesssim 10^{-5}$ Torr), a plasma discharge is formed by imposing a high negative voltage (typically 50-80 kV) on the grid 10 such that ions are created and then extracted from the plasma discharge between the grid 10 and the wall of the vessel 2. For neutron applications deuterium or deuterium-tritium mixtures are generally employed, giving 2.45MeV or 14MeV neutrons, respectively. For energetic proton

production, gas having a deuterium-helium-3 mixture is employed. With proper conditions, a grid design offering an actual transparency that is greater than the geometric transparency and radial alignment of grid openings for the two inner grids, can cause ion beamlets (microchannels) to be formed between the grid 10 openings, creating what is termed the "Star" mode, shown in Figure 2. A dense plasma core region is then formed in the center of the sphere where the beams converge, creating an intense fusion reaction rate in this core region. The microchannels have the dual advantages of aiding ion focussing and minimizing ion-grid collisions.

A unique plasma potential structure is created in the IEC plasma if the ion current is sufficient to create a strong virtual anode in the central plasma region. This potential accelerates and focuses electrons in the center core region, forming a virtual cathode, as illustrated in Figure 3. This structure results in a potential distribution across the device, termed a "double" potential well, that is very beneficial to IEC operation since energetic ions trapped in the "well" create a high fusion rate. In practice, broadened distribution functions lead to the simplified "double-well" structure of the type shown in Figure 3, where a virtual electrode structure in an idealized IEC configuration with monoenergetic ions and electrons and

negligible angular momentum is shown. The potential distribution structure will be broadened as both energy-angle distributions spread out in an actual system implementation.

As noted earlier, the basic IEC concept employs a grid design that creates a "Star" mode discharge with its ion microchannels. This approach provides simplicity, good ion focusing and improved grid life. The microchannels, which form due to the grid potential structure and corresponding ion "optics", improve ion focusing and lead to the extended grid lifetimes. At high ion currents, this improved focussing also aids the creation of a strong double potential well in the central core region, described earlier, leading to significantly increased fusion reaction rates.

A symmetric configuration, of the type ultimately needed for high yield operation, is used in present IEC devices that are being commercialized for portable NAA applications. Asymmetric designs are also possible and useful. For example, in a "jet" mode operation, asymmetric beams are trapped in the potential structure and redirected through a "hole" created in it by an enlarged grid opening, as described in PCT International Application No. PCT/US97/19306, which is incorporated herein by reference. This configuration has possible applications for materials processing and as a low power

thruster for space satellite orbit adjustments. Another non-fusion example involves efficient fullerene production from methane, as disclosed in PCT International Application No. PCT/US97/00147, which is incorporated herein by reference. In that case the IEC potential well structure is used to concentrate carbon ions in the deeper center trap, allowing hydrogen ions to move outward, enhancing formation of C-60 chains. The IEC device also can be used as an X-ray source, as disclosed in PCT International Application No. PCT/US97/19307, which is incorporated herein by reference.

An objective of IEC development is to improve neutron generation efficiency, eventually moving towards the high-yield devices needed for future power reactors and space propulsion.

Accordingly, an object of the present invention is to enhance the performance of the conventional IEC device to achieve higher neutron yields, thus extending applications to areas requiring higher neutron fluxes such as neutron tomography, isotope production, explosive/landmine detection, and oil well logging. In fact, the attainment of even higher reaction rates could, in principle, eventually lead to a fusion power device based on the IEC.

It is yet another object of the invention to retain the conventional IEC beam behavior, but to increase the ion currents well above the present 10-100 milliampere level in steady-state IEC operation.

It is a further object of the invention to provide a method of easily and efficiently generating repetitive pulses of high energy ions with a resulting production in high quantities of neutrons and/or protons.

SUMMARY OF THE INVENTION

The key to obtaining yet higher neutron yields is to retain the conventional IEC beam behavior and to increase the ion currents well above the present 10-100 milliampere level. Since the fusion reaction rate increases with the square or higher power of the ion current, if the ion currents can be increased into the multi-ampere range, fusion reaction rates will exceed those of present devices by several orders of magnitude. Also, at these levels, a double potential well is expected to form in the central core region, trapping energetic ions, thus increasing ion confinement, hence reaction rate and power efficiency.

In achieving this result, the present invention utilizes a gate-valve pulsing (GVP) technique that provides a practical method for achieving the high ion currents required for these high reaction rates, giving

time-averaged neutron and/or proton source rates in the range of 10^{11} - 10^{14}/sec.

The pulsed GVP-IEC of the present invention contemplates pulsing in accordance with two distinct techniques. A first is a low repetition rate GVP (LR-GVP) operation and a second is a tuned high-frequency pulsing, termed Resonant Ion Driven Oscillation (RIDO) GVP operation.

Structurally, both of the GVP-IEC designs employs a modified version of the steady-state spherical IEC configuration previously disclosed in US patent application S.N. 08/232,764. Specifically, both the LR-GVP and RIDO-GVP versions of the IEC utilize a "gate" grid system, comprising electron emitters, an electron guide grid, and a gate-valve grid, in combination with a pulsed voltage source, that provides the desired increase in ion currents.

In operation, the gate-valve grid of the present invention is initially biased to retain or "store" ions produced by electron-neutral collisions in the source region of the IEC device. Then the voltage on the gate-valve grid is suddenly decreased to enable extraction, acceleration and focussing of the "stored" ions by the central high-voltage cathode grid. After the desired pulse of fusion products (neutrons and/or protons) is obtained, the gate valve grid is returned to its original

bias state and the procedure repeated at a pulsed repetition rate, typically 100 to 1000 Hz for "low" repetition rate operation, that is sufficient to achieve the desired time average neutron/proton flux.

In the RIDO-GVP technique, the pulsing is run with a frequency tuned to the ion recirculation time of the system (typically in the MHz range). This tuning makes possible higher ion currents by ion bunching and superposition of recirculating ion beams. In this case the tuning is set in a specific GVP-IEC device by monitoring the neutron rate while sweeping the picked power supply through a range of frequencies, e.g. 1-10 MHz. Resonance with the device ion recircution frequency is signaled by a significant increase in neutron production. Once selected, this resonant frequency can be retained for subsequent operation of this particular device. Since the ion recirculation frequency depends on device parameter, the procedure must be repeated if a different GVP-IEC is used.

The advantage of the GVP-IEC concept, operating in either of these two modes, is the possibility of achieving higher fusion reaction rates and improved power efficiency while still using a relatively simple pulsing system compared to other possible ways of pulsing the IEC.

Previous IEC pulsing concepts typically have employed direct pulsing of the central-cathode or electron-emitter pulsing. Compared to the direct pulsing of the cathode, much lower pulsed voltages are required, e.g. 100 - 500 V for the gate-valve grid vs. 50 - 100 kV for the direct method. While pulsing the electron emitters also allows a relative low pulsed voltage, it does not provide for accumulation (storage) of ions prior to the pulse like the gate-valve grid approach does.

During operation of the LR-GVP, the gate-valve ion "injection" system utilizes electron emitters staged around the perimeter of the IEC chamber to provide a sustainable edge ionization source to generate ions. The location and number of emitters is selected to maintain a reasonably uniform election density in the ionization volume, typically requiring emitter separations equal to the election mean free path in the ionization volume. A fairly uniform density of ion are thus generated in this volume by electron-neutral ionization collisions However, instead of randomly entering the central potential well, the ions generated in this fashion are retained in the volume between the chamber wall and the gate grid until the voltage on the gate grid is suddenly reduced ~100 V ("opening" the gate valve). This allows the ions to flow into the core under the influence of the electric field generated by the high voltage (~50 -

100kV) cathode grid. Thus the central cathode potential serves as an ion extraction mechanism during this phase of the pulse.

RIDO-GVP operation offers even higher ion currents than low frequency GVP operation by bunching and combining ion beams. Accordingly, RIDO-GVP involves the addition of high frequency circuits and high precision for timing successive ion wave fronts to amplify the current in the plasma core. Collisional discharge mechanics will play in important role in ion distributions, thus requiring precise tuning.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustration of a conventional Inertial Electron Confinement (IEC) device used for neutron production.

Fig. 2 is a schematic illustration of a conventional IEC device operating in a "star mode" where plural microchannels of ions are formed and pass through the openings of a grid such that the effective transparency is greater than the geometric transparency.

Fig. 3 is an illustration of the potential variation that exists across the IEC device in relation to the anode shell and cathode grid. In this illustration it is assumed that the ion current is sufficient to produce a strong virtual anode which in turn accelerates and

focuses electrons in the central region, creating the double potential well shown in the core region.

Figs. 4a and 4b provide an illustration of a "gate" grid system (electron emitters, electron guide grid, and gate-valve grid) used in the present invention, together with an illustration of the potential profile for such structure and an illustration of the ion trajectory and ionization regions within the IEC device. Note the potential profile of the device during the standby mode (gate valve grid closed), the ionization region between the second and third grid, and inner cathode "fall" region where a step potential gradient occurs between the gate valve grid and the cathode.

Figs. 5a and 5b are illustrations of voltage vs. radius from the center line of the IEC device incorporating the present invention, where the gate potential is raised, and a device where the gate potential is lowered, respectively. Note that in the latter condition, the fall potential penetrates (extends into) the ionization region.

Fig. 6 is a graphical interpretation of the underlying concept of the present invention, showing the presence of "wave packets" of ions moving back and forth (recirculating) between the outer grid and inner grid. As illustrated, tuning the potential frequency on the gate valve grid to match the recirculating frequency of

the ion packets superimposes packets, increasing their ion density.

Fig. 7 is an illustration of the power, based on the applicable voltages and currents, that are applied to the three-grid IEC device incorporating the present invention, including operation in the steady state and pulsed modes.

Fig. 8 is a circuit diagram of a power supply system for the GVP- IEC, including a pulse forming network used in the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The IEC-GVP device 11 is illustrated in Fig. 4a and comprises a structure similar to the IEC device of Fig. 1, including a grounded conductive vessel 12, serving as an anode, and a central cathode or primary grid 13 that is connected to a high voltage source (not shown). In addition, an intermediate second grid 14 and an outside third grid 15 are disposed concentrically with the central cathode 13 within the vessel 12. Electron extractor/emitter devices 16 are disposed substantially symmetrically about the perimeter of the vessel and include electron extractor deflector grids 17 and electron emitters 18 that contribute to the enhanced timed ion flow in the device.

The basic operating principle of the GVP-type IEC is to flood the exterior region 23 of the device (i.e. the ionization volume between the outer grid 15 and the middle grid 14 in Fig. 4b) with electrons "boiled off" from multiple electron emitters 18 of a conventional design that are placed strategically around the device perimeter. The placement of the emitters is based on the mean distance of electron travel before collisional loss. The acceleration grids in the emitter assemblies draw the electrons into the vacuum chamber where they next encounter the positively biased guide grid 15. This grid 15 serves to redirect the electron trajectories into a narrow shell-like volume circumferentially disposed around the inner surface of the vessel wall, defining an ionization region 23 where electrons interact with the background gas and produce ions via collisional ionization. These electrons 19 travel circumferentially and oscillate back and forth across the ionization region 23, gradually slowing down by impact ionization collisions with background neutral gas until they are finally lost by recombination or collisions with the grids or vessel wall. Ions generated by electron collisions in this region will experience little or no net force since no applied electric field is present. In this state then, the high potential on the cathode is "shielded" out of the ionization region by the potential

on the gate-valve grid 14. Consequently, the ions only slowly diffuse out of the ionization region, allowing a high density of ions to build up in that region. This condition can be viewed as a "storage" of the ions in preparation for the subsequent generation of an ion pulse.

To pulse the IEC, the middle anode grid 14, serving as a "gate", has a potential applied to it that is quickly ($\lesssim$100 μs) decreased by 100V to 1 kV. This allows the central cathode 13 potential of 10-100 kV to penetrate into the outer ionization region 23 and extract the ions "stored" there. The gate-valve grid 14 potential is then switched back to its original value after the stored ion group has left the ionization region, i.e. within a period of 500 n.s. or shorter. These extracted ions accelerate into the center cathode region 21 to the full-applied potential of the central cathode 13. The accelerated ions will converge to a point in the core region of the device forming a dense central core plasma 21 where fusion reactions occur, thereby generating high-energy protons and neutrons from the D-D (or other fusionable gas) fusion reaction. The spherical shell 23 of ions around the grid reforms again as the inertia of the ions carry them through the inner fall region 22 and back up the applied potential until they come to rest at a potential equivalent to that at

their point of generation via collisional ionization. Some ions are lost via reactions, charge-exchange and grid collisions in this process. However, many are reaccelerated back into the central plasma core region 21 and continue to recirculate. This circulation of ions continues until their population is significantly depleted (<25% of original). Since the ion recirculation time is short (ms time scale), the gate-valve grid potential is maintained at its lowered value for milliseconds to take full advantage of increased fusion reactions created by the recirculating ions. When the grid openings on the cathode grid are designed for star mode operation as disclosed in U.S. Patent Application SN 08/232,764, and these openings are orientated such that the align radially with the openings in the gate valve grid 14, ion microchannels (characteristic of the star mode) will be formed with the recirculating ion flow, providing improved focusing and higher reaction rates in the core. The potential profile across the GVP-IEC prior to opening the gate-valve grid is seen in Fig. 4a, with operating potentials ranging between +100V to -100kV, as shown, but with a flat potential (negligible electric field) in the ionization region.

Structurally, it is preferable that a sufficient number of the holes in the three grids are oriented with

respect to each other in a radial direction so that they will have a high geometric transparency and will be able to sustain a high effective transparency to ions, such that the requisite number of ion spokes for the desired star mode or halo mode can develop within the vessel. The grids themselves may be of a vane or wire-type structure, as is known in the art, and at least the cathode would have the requisite h/R parameter, as disclosed in U.S. application S.N. 08/232,764, wherein h is the height difference between a grid's spherical surface and the plane of the grid, and the R is the grid radius. The pressure within the vessel can be maintained by a getter or pump, or a combination of such conventional techniques.

Figures 5a and 5b are schematic illustrations of ion extraction from ionization region by penetration of the central cathode potential after the gate voltage is lowered in a three-grid embodiment as shown in Figs. 4a and 4b. As already disclosed, the exterior two grids 14 and 15 in the system serve two purposes: a) the external grid 15 guides electrons that are extracted from the electron emitters such that in combination with the gate-valve grid 14, the electrons are confined to flow through and circumferencially around the ionization region. Thus, the combination of the two grids creates a minimal for electrons to transit and allows for ionizations to

remain localized in the field-free region, and b) the middle "gate" grid 14 serves as the valve to selectively admit groups of ions into the core region. As seen in Figure 5a and 5b, the gate-valve grid potential can be raised and lowered, allowing the central cathode potential to penetrate into the ionization region and extract ions. The figure shows ions (schematically shown as dots) "stored" in the ionization region where they are born until the gate value potential is suddenly lowered and they are accelerated towards the center by the potential gradient ("fall region") created by the potential in the central cathode grid.

One significant advantage of the three-grid, emitter-assisted, GVP-IEC system is that the ions always start out in the ionization volume near the vessel wall and thus accelerate to their full-applied potential energy at the central core plasma region, leading to a reduced ion energy spread, greater efficiency and improved focusing. Additionally, since the plasma discharge is supported by electron generator emission (vs. secondary electron emission from the grids), the background gas pressure can be greatly reduced, significantly lessening ion isotropization effects from scattering collisions and energy losses from charge-exchange collisions. Further, as indicated earlier, the pulsed voltage required for the gate-valve grid is

generally low (<1kV) compared to directly pulsing the central anode, which would require pulsing voltages of 10's of kV. This greatly simplifies the pulsed power supply technology and reduces electrical insulation problems.

An extension of the basic GVP-type IEC operation involves synchronization of the injection of ions towards the inner core with the natural ion circulation frequency in the system, i.e. setting the frequency for reducing the GVP potential to coincide with the ion circulation frequency (around 0.5-50 MHz). This form of operation has been named Resonant Ion Driven Oscillation (RIDO). In this way, newly generated ions converge towards the inner core at the same time that the recirculated ions arrive at their turning points. Thus, all of the recirculating ion currents are effectively superimposed towards the inner core of the device, allowing them to be accelerated from the device perimeter and converge to the center. Consequently, very large peak densities can form at the ion transit frequency (around 0.5-50 MHz), providing for an ultra high time-average fusion generation rate.

Figure 6 shows a graphical interpretation of the RIDO-GVP process using an electron-emitter assisted three-grid IEC of the type shown in Fig. 4, where there is a superposition of ion fronts and spherical symmetry.

In the RIDO operation, the extraction of ions from the exterior region is timed exactly so that when a previous ion wave front returns to its original starting location, a new successive wave packet of ions is introduced and superimposed onto the previous group of ions. The combined ion population is then extracted and focused into the central core region again when the gate valve potential is reduced, i.e., the gate is "opened". Ion losses during transit eventually limit the build up during this process, such that the ion density passing through the central core reaches a "saturated" (constant) value for subsequent pulses. This process effectively magnifies the peak ion current passing through the central core region. Consequently, the central core ion density is increased by several orders of magnitude, since the ions in the spherical shell all arrive simultaneously at the core region of the device. This process leads to gains in fusion power rate ($P_{fusion} \sim n_{ion}^2$) over a conventional IEC plasma discharge that are even larger than those available from the LR-GVP operation.

With the high ion currents achieved with either the LR-GVP operation or with RIDO-GVP operation, ion currents above those required for double well formation (Fig. 3) can be achieved. This permits ion trapping and ultra high ion densities in the center core, further enhancing reaction rates. The effect of double-well formation has

been studied experimentally in the steady-state IEC and has been shown to lead to a higher scaling of fusion reaction rates with the applied current. The effect is easier to create with the high currents achieved in the LR-GVP device than in the steady-state IEC device.

The power supply requirements for a preferred embodiment of the GVP-IEC are illustrated in Figure 7. A pulsed power supply 35 having a value of 100V and oscillating between 0 and 1kV with a current in a range of 0-100mA, is used to switch the potential of the gate (middle) electrode 36 on and off. A steady-state supply 37A, having a power range of 0-100kV is connected to the cathode grid 38 and is operative to generate high central cathode voltages (i.e., up to 100kV) and small currents (in a range of 0 to 100mA). A transmission-line pulsing system 37B also may be connected to the cathode grid 38 for very high current operation (several amps and above) at similar high voltages (pulsed operation is used because in current levels » 1 amp can best be achieved in transient operation). Finally, several high-current emitter power supplies 31 having a range of 0-50A are connected to drive the segmented discharge elements 32. For standard operation of the gate-valve grid, the gate power supply pulses at a relatively low frequency ($<10^3$ Hz).

GVP type operation can also be extended to other modes of operation of the IEC device, for example the halo mode and jet modes of operation as described in prior IEC patents. The basic principles described here carry over directly.

For RIDO operation, high frequency pulsing (0.5-50 MHz) is employed. RIDO type operation and requires consideration of grid transparency issues, discharge species time constants, energy spreading and collisional losses, and space charge effects.

In summary, GVP operation allows an improvement over the conventional IEC design in obtaining higher fusion reaction rates by achieving high ion densities in the central plasma core during a pulse. Even higher densities can be achieved via RIDO-GVP where the superposition of ion fronts simultaneously increases the power efficiency by accelerating ions in bunches or groups.

The pulsed power supply 35 that is employed for the GVP-IEC may use conventional technology, such as the pulsed power unit developed for direct pulsing of the cathode, as disclosed in Y. Gu, M. Williams, R. Stubbers, G. H. Miley, "Pulsed Operation of Spherical Inertial-Electrostatic Confinement Device," *12th Topical Meeting on the Technology of Fusion Energy*, (Reno, NV, June, 1996), ANS, LaGrange Park, IL, 128 (1996). Cathode pulsing has

the disadvantage of pulsing the main cathode to a high voltage, as contrasted to the Gate-Grid design disclosed herein, where the main cathode is maintained in steady-state at a high voltage while the gate grid is pulsed at a low voltage. As a result, the desired current and voltage per pulse may reach or exceed the 10^8 n/s level (50-kV pulse with 3.2 A of pulse-current and a duty factor of 1% e.g. 0.1-ms pulse length × 100 pulses/sec) with a standard pulsed power supply connected to the main cathode.

The fundamental operating principles of the pulsed power unit have not changed since the original description by Gu et al., as published in "Ion Focus Via Microchannels; in Spherical Inertial-Electrostatic Confinement and Its Pulsed Experimental Results," presented at 1995 IEEE International Conference on Plasma Science, 1995, pp. 266-267. However, that power unit 40, which has an input 41 coupled in series to a choke 42, diode 43, pulse forming network 48, pulse transformer 49 and the IEC equivalent resistance Rplasma 50, has been upgraded to achieve the desired pulse currents, voltages, and repetition rates cited above. In particular, the main switch 45, as illustrated in Figure 8, has been upgraded by using an ignitron, rather than a thyratron, that responds to the trigger pulse 44 so that the pulser can deliver higher currents. A diode 46 and coil 47 are

connected in parallel to the switch 45. Also the step-up ratio of the pulse transformer 49 has been increased from 1:7 to 1:10 to allow better matching with the IEC plasma along with higher voltage pulses. The component ratings are adjusted to provide either the standard low frequency (10 - 1000 Hz) LR-GVP operation or the high frequency (1 - 50 MHz) RIDO operation.

While pulsed neutron sources have been known in the prior art, the basic principle of the GVP-type IEC is distinctly different from these devices. Fentrop's neutron generator is basically a beam solid target system that can operate in steady-state or in a pulsed mode (U.S. patent No. 3,546,512). It is in effect a large ion accelerator - target device. There is significant difference between the GVP--IEC and this system, based on the GVP-IEC's control of the beam-plasma discharge, operation with staged ionization and extraction regions, and absence of a magnetic field for ionization. Croitoru (U.S. Patent No. 3,609,369) utilizes several ion sources that are localized and positioned around a solid target. Again, plasma discharge control is not involved. Operation in a continuous or pulsed mode is entirely for purposes of ion gun operation. Thus it's operation, unlike GVP-IEC, has no provision for ion storage, injection timing or resonant oscillation. Culver (U.S. Patent No. 3,996,473) developed a device intended for

pulsed operation for analysis of materials involving diagnostic techniques such as prompt gamma spectroscopy. His pulsing method does not directly involve the neutron generator's operational physics (such as microchannel beam formation and multiple well formation in the core in the GVP-IEC). Further, pulsing and it's control in his device has no direct interaction with on the pulse timing control (e.g. ion storage, injection timing, etc,) as occurs in the case of the GVP- IEC. Bussard's invention on the ICC effect for enhancing IEC operation (U.S. Patent 5,160,695) mentions the usage of resonant coupling in their system. It is Bussard's claim that ions can be reflected between ion acoustic barriers and trap ions in the IEC core region. This type of ion control is dependent on obtaining high ion currents, but does not discuss a method for obtaining them such as the GVP method disclosed here. While GVP-IEC operation involves resonant tuning, the RIDO resonance involves the ion recirculation frequency, and is controlled through timing of the storage and injection of ion currents by the gate-valve grid. This represents a significant departure from Bussard's acoustic barrier resonance concept, although the two approaches could be combined for use in a single device.

The GVP-type IEC provides a significant edge over conventional IEC technology or solid-target based neutron

sources. The increased neutron yield would open up new areas of commercialization in the regimes of medical research, neutron tomography and isotope production. The GVP-IEC mode offers very high reaction rates that would be especially desirable for fusion electrical power production or fusion space propulsion.

Current steady-state basic IEC operation produces fusion neutron yields on the order of 10^6-10^7 D-D fusion neutrons/second. Pulsed versions of the basic IEC with direct pulsing of the cathode grid have yielded neutron yields on the order of 10^7-10^8 D-D fusion neutrons/sec (time averaged). The incorporation of the GVP-IEC concept adds the capability to increase these yields by orders of magnitude, the immediate goal being 10^{12} - 10^{14} D-D fusion neutrons/sec (time averaged). RIDO type operation can achieve even higher yields, the limit being set by possible instabilites due to the non-Maxwellian nature of the intense beam-plasma type discharge.

The GVP-IEC concept also has several key advantages over competing non-IEC concepts. The primary advantage is efficiency. Since the ions accelerate into the core region at the same time and the fusion reaction rate goes as the density squared, this leads to an increased fusion product output per unit energy input. Another advantage is simplicity. Additionally, the RIDO-driven IEC maintains a beam-beam reaction capability which

increases the devices efficiency for reaching advanced fuels such as D-He3 as opposed to devices operating by interaction of Maxwellian populations of ions.

A summary of a 25-MW_e power plant design using GVP-IEC principles is given in Table I. The size represents the radius of the spherical vacuum chamber wall, exclusive of cooling systems. Weights are for the IEC unit alone and for the entire reactor system. Most of the weight is accounted for by the large vacuum chamber wall. The relatively low weight of the unit, including the direct converter, is one of the attractive features of the GVP-IEC power plant, implying competitive costs for materials and construction. In fact a GVP-type IEC reactor would have a higher mass power density than conventional magnetic or inertial confinement fusion systems, suggesting costs much more competitive with a light water reactor than those projected for other fusion reactor designs.

Table I. Characteristics of a 25-MW_e power plant utilizing GVP pulsed power operation and I_{ion}^3 scaling

Input Power	4.80
Size/radius(m)	6.49
IEC total weight (tonnes)	2.84
Total reactor estimated weight (tonnes)	210

While the present invention has been described in accordance with certain preferred embodiments, the present invention is not limited thereto and its scope is defined in accordance with the appended claims as interpreted in accordance with applicable principles of law.

What is claimed is:

1. A device for generating pulses of high ion currents in an inertial electrostatic confinement device comprising:

a conductive vessel defined by a wall and biased to serve as an anode, said vessel having a fusionable gas disposed therein;

a plurality of electron generators placed near an internal surface of said vessel wall for emitting electrons into said vessel;

a first grid, comprising a highly transparent, substantially spherical structure centrally disposed within said vessel and defining a central volume;

a first potential source for supplying an electric potential to said first grid such that it serves as a central cathode, whereby the potential between the cathode and anode causes the ions to accelerate towards the cathode, the increased energy ions interacting among themselves and with neutral gas atoms as they converge to form a high ion density within the central volume;

a second grid, comprising a highly transparent positively biased structure disposed near the vessel wall to guide emitter electrons generally within a circumferential ionization volume defined with respect to said vessel wall;

a second potential source for applying an electric potential to said second grid such that electron trajectories are within the circumferential ionization volume;

a gate valve grid apparatus, comprising a third grid that is a highly transparent spherical structure disposed within the second grid but outside the first grid, and a third potential source for applying a time dependent voltage on said second grid so as to repetitively release groups of ions, which are accelerated due to said anode and first grid acting as a central cathode, said apparatus being operable such that the potential applied from the third potential source to the third grid can be varied to alternately shield or expose ions in the ionization volume to a potential created by the first grid;

whereby periods of intense fusion reactions are created.

2. The device as set forth in Claim 1 wherein each said electron generator further comprises a source of electric current to heat said electron assemblies.

3. The device as set forth in Claim 1 wherein said electron generator further comprises a fourth potential source for applying a voltage to extract electrons from said electron generators.

4. The device as set forth in Claim 1 wherein the said first grid, said second grid and said third grid are rigid self-supporting structures, having plurality of openings through which ions and electrons may flow, and at least one of said structures is held in place within said vacuum vessel by electrically insulated stand-off structures extending out from the vessel wall.

5. The device as set forth in Claim 4 wherein one of said first, second and third grids comprise at least one of a wire structure and vane-type structure.

6. The device as set forth in Claim 1 comprising at least two electron generators disposed substantially symmetrically about the inner surface of said vessel wall.

7. The device as set forth in Claim 6 comprising two to eight electron generators.

8. The device as set forth in Claim said electron generator comprises both an electron emitter and an electron extractor.

9. The device as set forth in Claim 2 wherein said conductive vessel is held at ground potential while the first, second and third grids comprise conductive electrodes having connected thereto respective power leads, passing through the spherical vacuum vessel and

electrically insulated therefrom, and being connected to a respective source of electric potential for each grid.

10. The device as set forth in Claim 2 wherein said gate-valve grid is connected to a circuit for maintaining a biased positive potential of 50 to 300 volts plus superimposing a pulsed negative electrical potential of magnitude 100 volts to 1 kilovolt for 1 μs to 1 ms time duration with repetition rates of 1 to 1000 cycles per second.

11. The device as set forth in Claim 10 wherein the repetition rate of the pulsed negative electrical potential on said third grid is adjusted to be in resonance with an average ion recirculation frequency within a range of 0.1 to 50 MHz.

12. The device as set forth in Claim 1 wherein said conductive vessel is a hermetically sealed metallic shell.

13. The device as set forth in Claim 1 wherein the source of electric potential for said cathode grid provides a negative potential within a range between 1 kV to 150 kV.

14. The device as set forth in Claim 1 wherein the source of electric potential to cathode grid provides driving pulsed ion currents greater than 1 ampere.

15. The device as set forth in Claim 1 wherein said grids have geometric transparencies of greater than or equal to 90%.

16. The device as set forth in Claim 1 further comprising means for maintaining the fusionable gas pressure in said spherical vacuum vessel at less than 10^{-5} Torr.

17. The device of Claim 3 wherein said fourth potential source employs driving currents with peak values varying in a range between 5A to 25kA.

18. The device in Claim 2 wherein the current source for applying electric current to heat said electron emitter provides a current that varies within a range between 1 A to 20 A inclusive.

19. The device in Claim 3 wherein the source of electric current to heat said electron emitter employs a driving voltage and current that applies between 5W and 400W of power.

20. The device in Claim 1 wherein each of said first, second and third grids comprise at least one of a wire structure and a vane-type structure, said grids having openings that are aligned radially and at least the first grid is defined by h/Rc, where h is the height difference between a grid's spherical surface and the plane of the grid, and the R is the grid radius.

21. The device as set forth in claim 1 wherein said grids have openings designed such that ion microchannels are formed during said pulsed plasma discharge.

22. A method for generating pulses of high ion currents in an inertial electrostatic confinement device comprising a conductive vessel biased to act as an anode and containing a plurality of nested highly geometrically transparent grids, a source of electrons, a source of electric power and a fusionable gas, comprising:

generating an electric field defined by potential applied to said anode and grids;

establishing an ionization region within said vessel;

generating electrons within said vessel and causing the electrons to flow within the ionization region;

generating and sustaining ions within said ionization region using said electrons;

periodically releasing ions from said ionization region; and

accelerating and focusing said released ions by said electric field.

23. The method of claim 22 wherein the releasing step is at a frequency timed with the characteristic ion recirculation of the system.

24. The method of claim 22 wherein the releasing further comprising synchronizing the injection of ions toward the inner core of the vessel with the natural ion recirculation frequency in the system so that newly generated ions converge toward the inner core at the same time that the recirculated ions arrive at their turning points.

25. The method of claim 22 wherein said releasing step further comprises switching on and switching off the potential to one of said grids acting as a gate to allow the central cathode potential to penetrate into the ionization region and extract the low energy stored ions.

26. The method of claim 22 the time of said releasing step is long compared to the ion recirculation time.

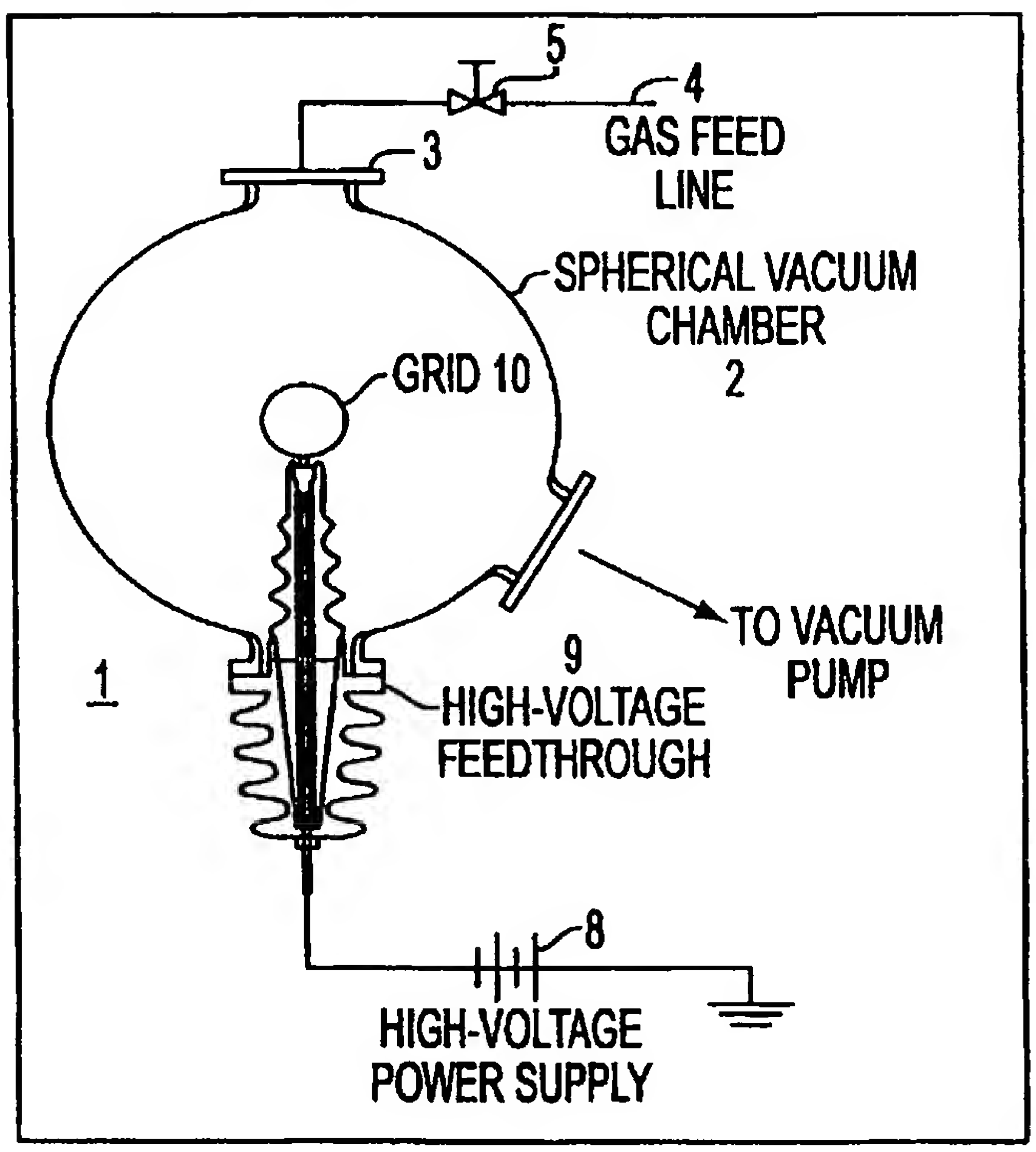
5
4
GAS FEED LINE
3
SPHERICAL VACUUM CHAMBER 2
GRID 10
TO VACUUM PUMP
9
1
HIGH-VOLTAGE FEEDTHROUGH
8
HIGH-VOLTAGE POWER SUPPLY

FIG. 1

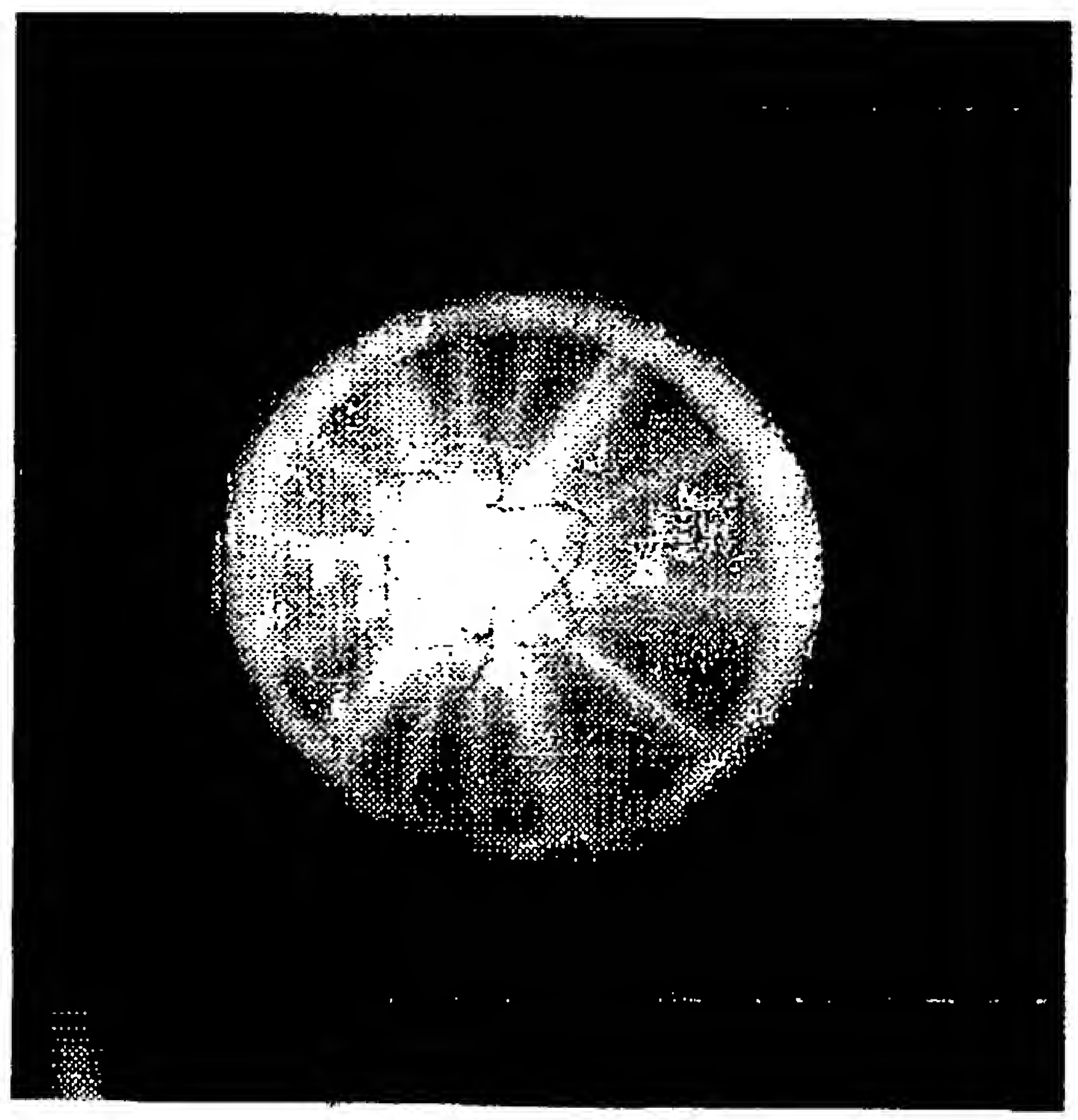

FIG. 2

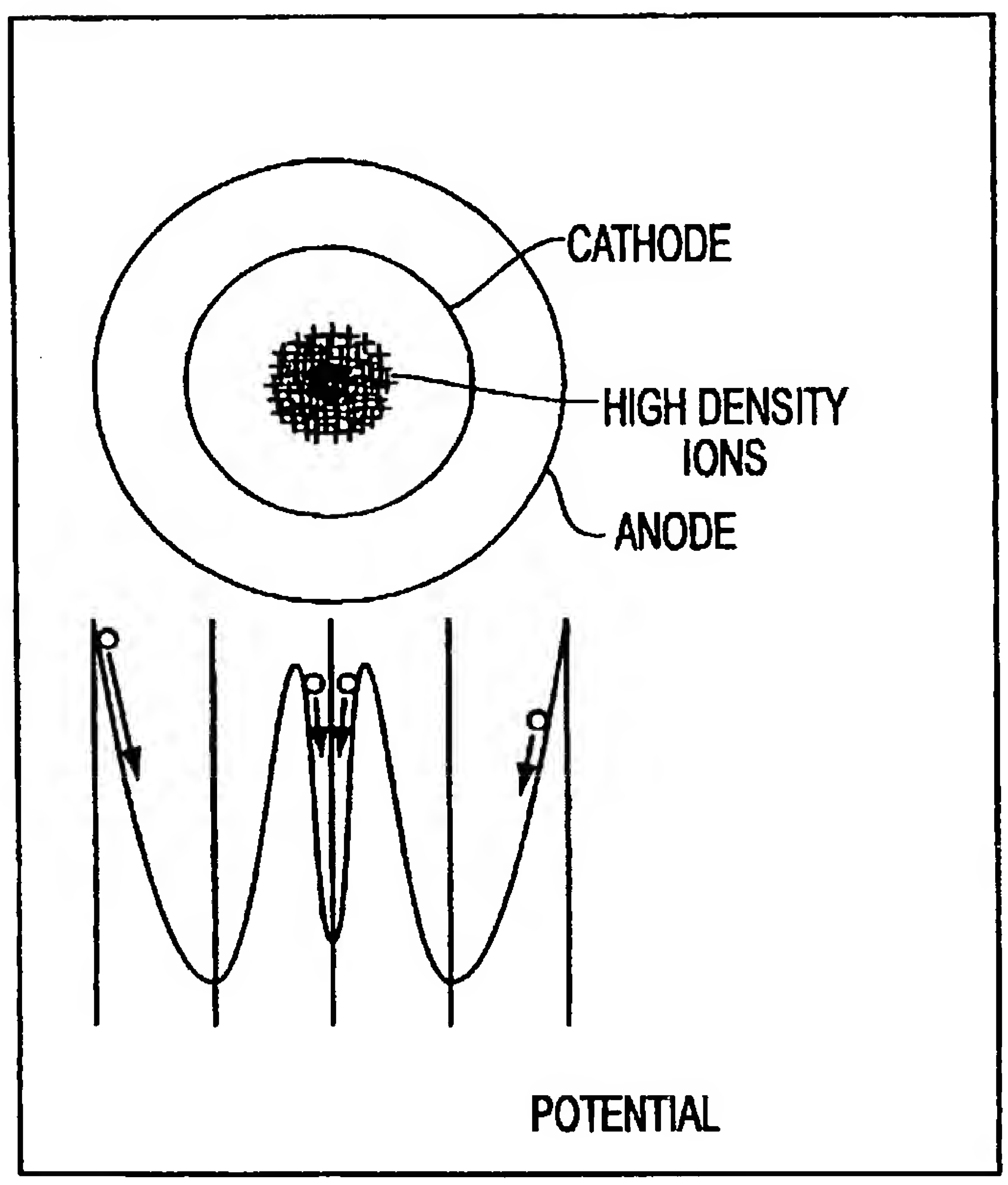

FIG. 3

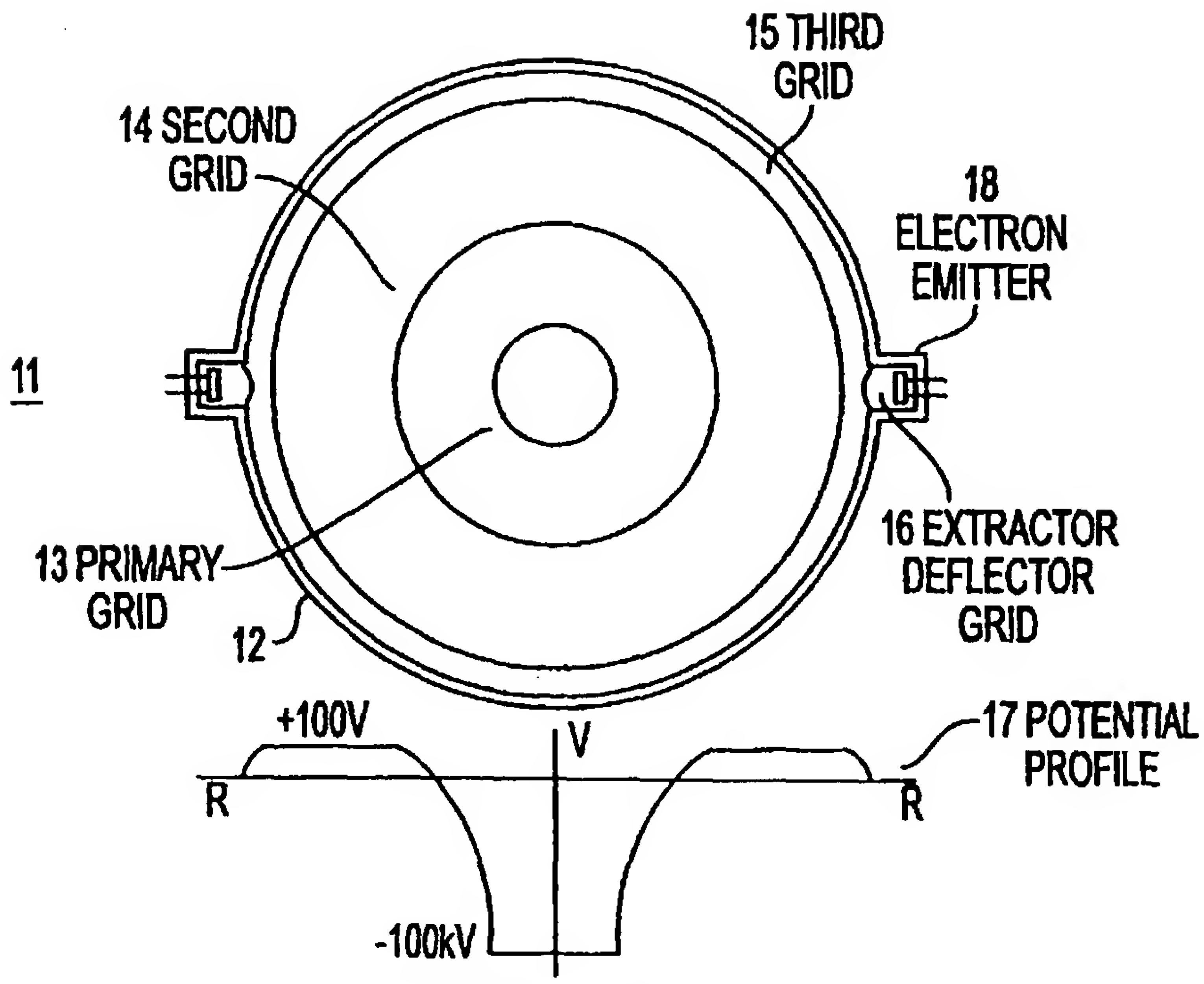
15 THIRD GRID
14 SECOND GRID
18 ELECTRON EMITTER
11
16 EXTRACTOR DEFLECTOR GRID
13 PRIMARY GRID
12
+100V
V
17 POTENTIAL PROFILE
R
R
-100kV

FIG. 4A

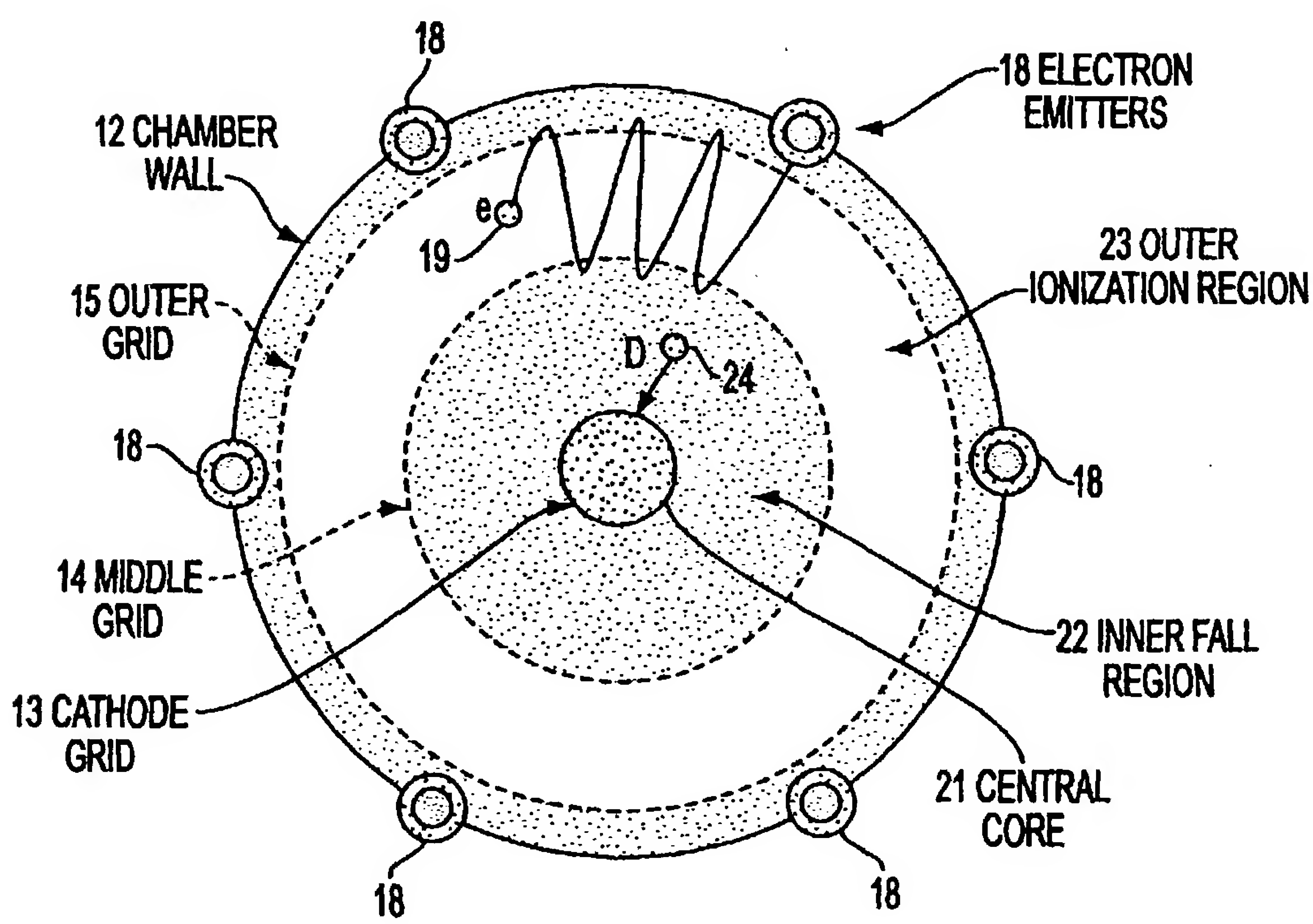
18
18 ELECTRON EMITTERS
12 CHAMBER WALL
e
19
23 OUTER IONIZATION REGION
15 OUTER GRID
D
24
18
18
14 MIDDLE GRID
22 INNER FALL REGION
13 CATHODE GRID
21 CENTRAL CORE
18
18

FIG. 4B

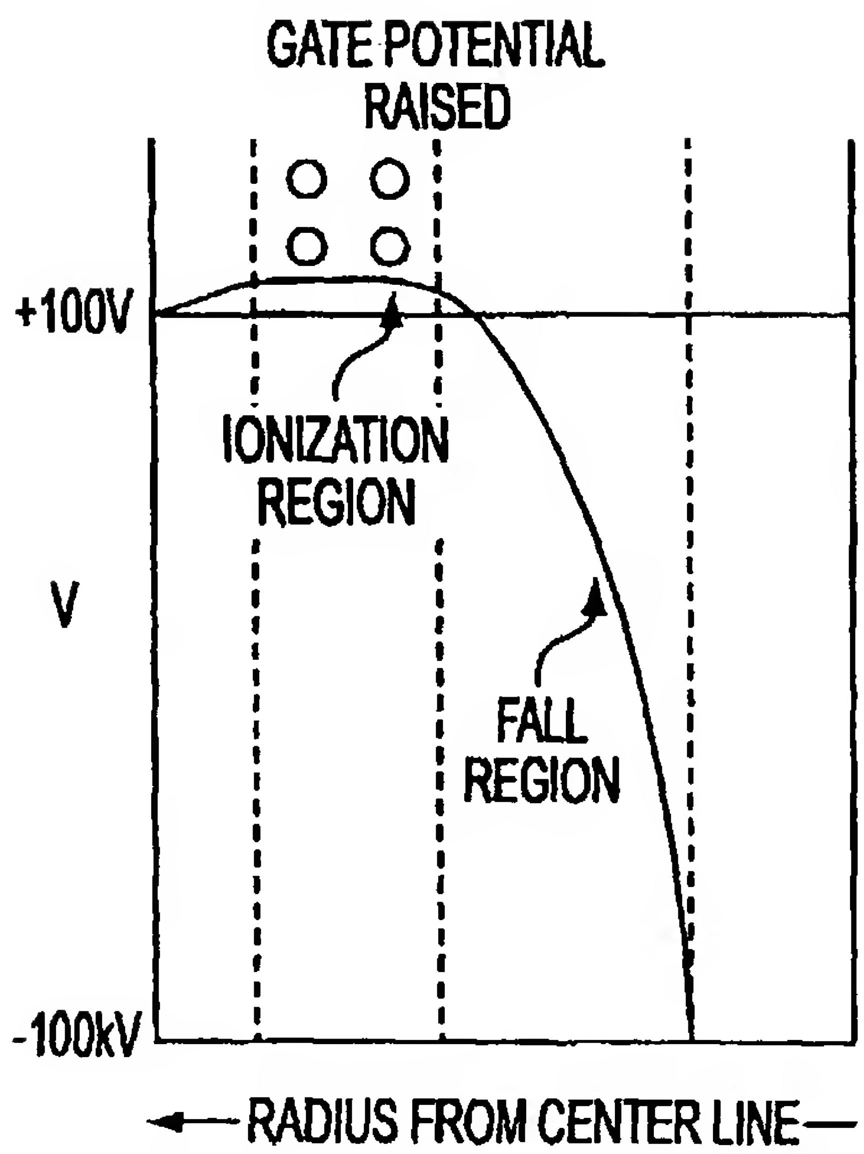

FIG. 5A

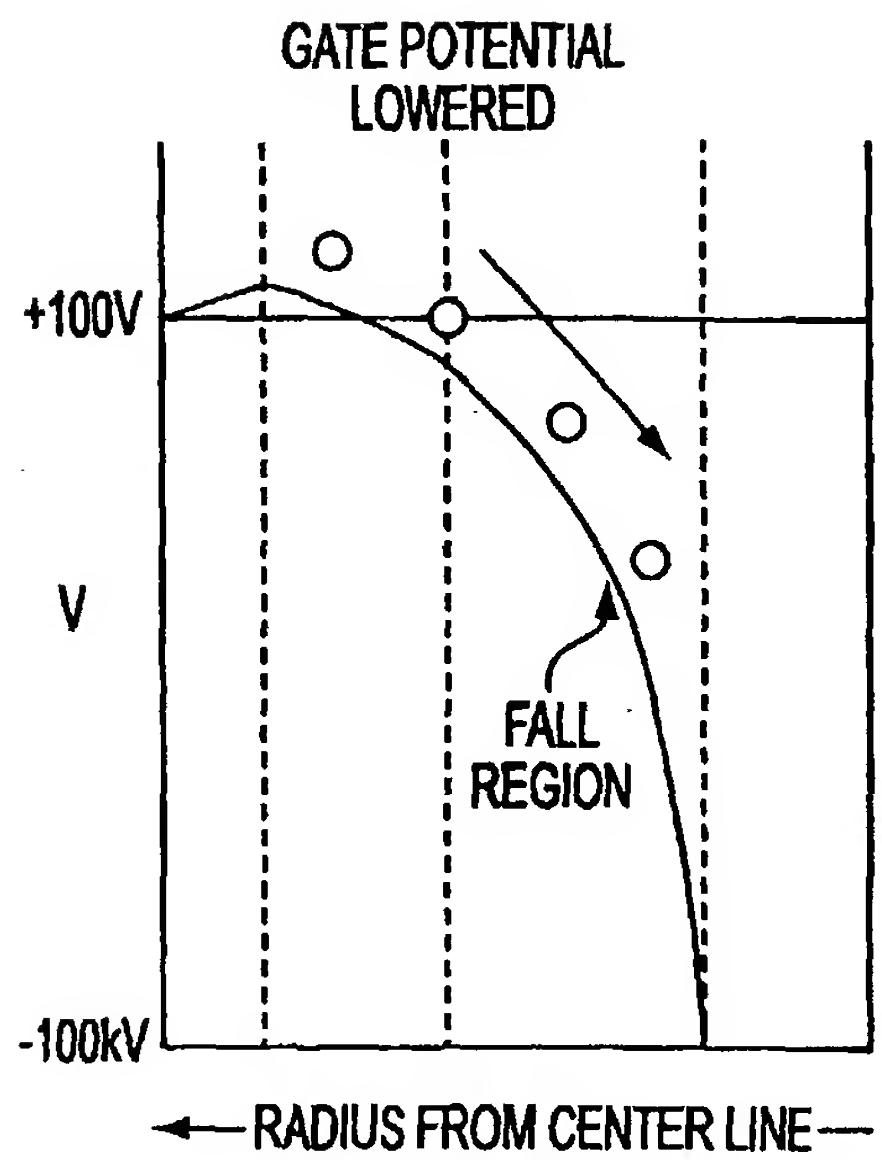

FIG. 5B

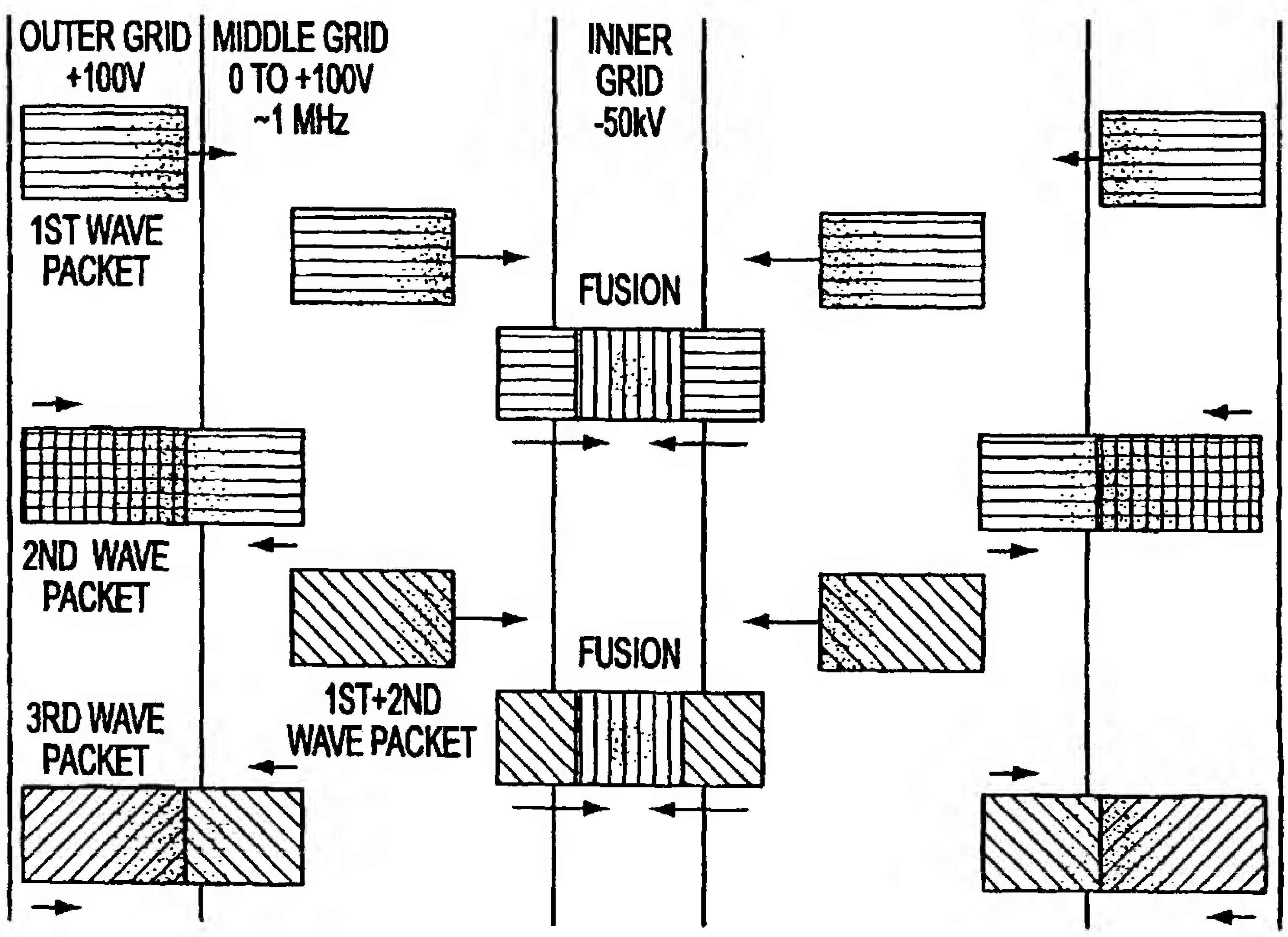

FIG. 6

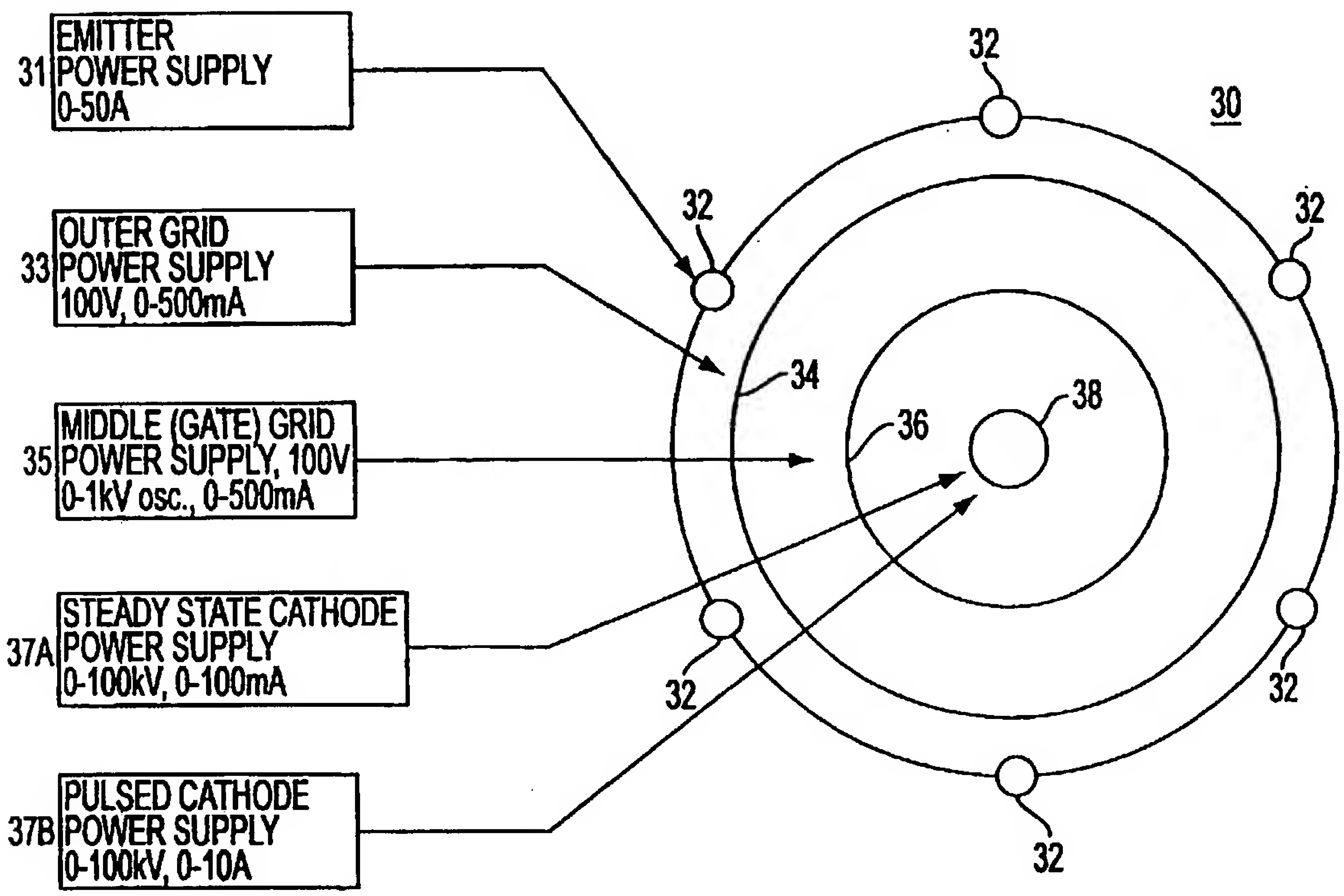
31 EMITTER POWER SUPPLY 0-50A
33 OUTER GRID POWER SUPPLY 100V, 0-500mA
35 MIDDLE (GATE) GRID POWER SUPPLY, 100V 0-1kV osc., 0-500mA
37A STEADY STATE CATHODE POWER SUPPLY 0-100kV, 0-100mA
37B PULSED CATHODE POWER SUPPLY 0-100kV, 0-10A
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FIG. 7

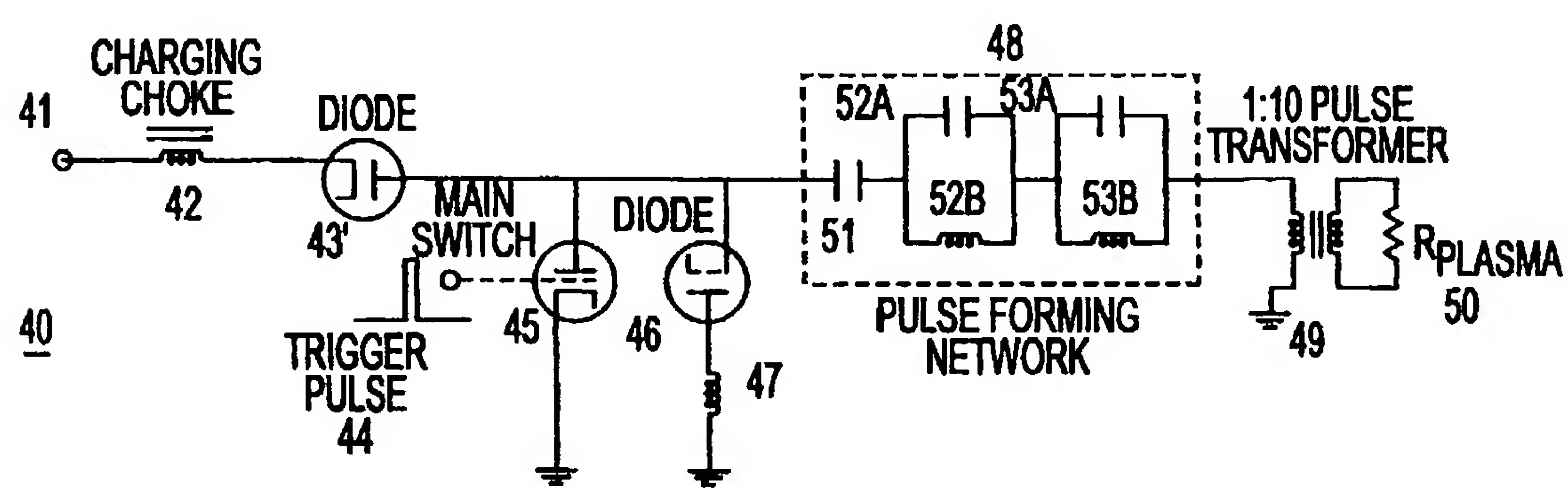
41
CHARGING CHOKE
42
DIODE
43'
MAIN SWITCH
TRIGGER PULSE
44
45
DIODE
46
47
40
48
52A
53A
51
52B
53B
PULSE FORMING NETWORK
1:10 PULSE TRANSFORMER
49
RPLASMA
50

FIG. 8